APL-UW Deep Water Propagation: Philippine Sea Signal Physics and North Pacific Ambient Noise and NPANL Support

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LONG TERM GOALS

Understand how the fundamental statistics of broadband low-frequency acoustical signals evolve during propagation through a dynamically-varying deep ocean, and how the oceanic ambient noise field varies throughout deep ocean battlespaces.

OBJECTIVES

Current models of signal randomization over long ranges in the deep ocean were developed for and tested in the North Pacific Ocean gyre. The first objective of this research is to determine the validity of these models in a region with different oceanographic features, specifically the Philippine Sea. The second objective is to continue an 18-year long experiment utilizing the North Pacific Ambient Noise Laboratory to determine whether models of oceanic ambient noise capture the spatial and temporal trends observed across the basin.

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APPROACH

Philippine Sea Analysis Our approach utilizes a combination of at-sea measurements, theoretical modeling and computational simulations. Our primary measurements are two 60 h transmission exercises over a range of roughly 500 km. We transmitted the signals: the acoustic receptions (and associated receiver details) are provided by Worcester at Scripps, and the environmental measurements at the receiver provided by Colosi at the Naval Postgraduate School. One exercise used the HX554 source and a signal with carrier frequency 81.88 Hz, and the other used the "multiport" source and two simultaneous signals with carriers at 200 and 300 Hz. Ganse is processing the multiport data. Each multiport signal had its own m-sequence law, allowing complete separation of the two signals in code space. Henyey provides critical guidance in our theoretical approach. Here, we assume the acoustic wave equation is valid, and use Monte Carlo simulations as guides — and benchmarks — for analytical expressions describing the evolution — i.e., the "physics" — of statistical properties of the acoustic wavefield. To attain the "applied" objective of accurately predicting at-sea performance, Henyey also provides guidance in the specification of "good" oceanographic models.

North Pacific Ambient Noise Laboratory (NPANL) Our primary approach involves several ambient noise collection protocols, involving single and multi-channel data acquisition 24/7/365 except for outages, on APL computers located at a remote facility. The hydrophones are located in the North Pacific basin. Data collection was suspended indefinitely in March 2014 by direction from the U.S. Navy until prior APL-USN agreements have been reviewed.

WORK COMPLETED

Philippine Sea Analysis

- We sent the entire RR1006 CTD dataset (this was the APL 2010 Philippine Sea cruise) to Peter Worcester. This included 55 CTDs in both original "raw" SeaBird format and a format post-processed at-sea to the Colosi NPAL specification.

- We sent a manuscript on a three-way comparison between the White at-sea measurements of log-amplitude variance and Monte Carlo predictions of log-amplitude variance [1] and Munk-Zachariasen theory predictions [2] to co-authors for comments. (Results were presented in last year's report.)

- We reviewed the engineering data files sent to us by SIO for the navigation of the DVLA STAR controllers over the period of the APL transmissions. The navigation solutions (i.e., $\{x(t), y(t), z(t)\}$ for every hour) have previously been determined and distributed by M. Dzieciuch, SIO. We find that we can generally recreate the Dzieciuch solutions. There are some outliers in the Dzieciuch solutions, primarily for the deeper controller, which we were able to trace to incorrect identification of navigation signal path (i.e., bounce versus direct path.) Correcting for this feature provides us with a cleaner navigation solution. See Fig. 1 for examples.

  We implemented a simple user interface to the navigation solutions that provides the (x, y, z) position for *any* time t, not just the solution at the time of the navigation event. An example usage of this interface in Matlab is shown in Fig. 2

- An undergraduate student, Mr. Robin Mumm (junior, physics), was hired for some repetitive routine data-organization tasks. First, he computed the hourly spectrogram for every hour that

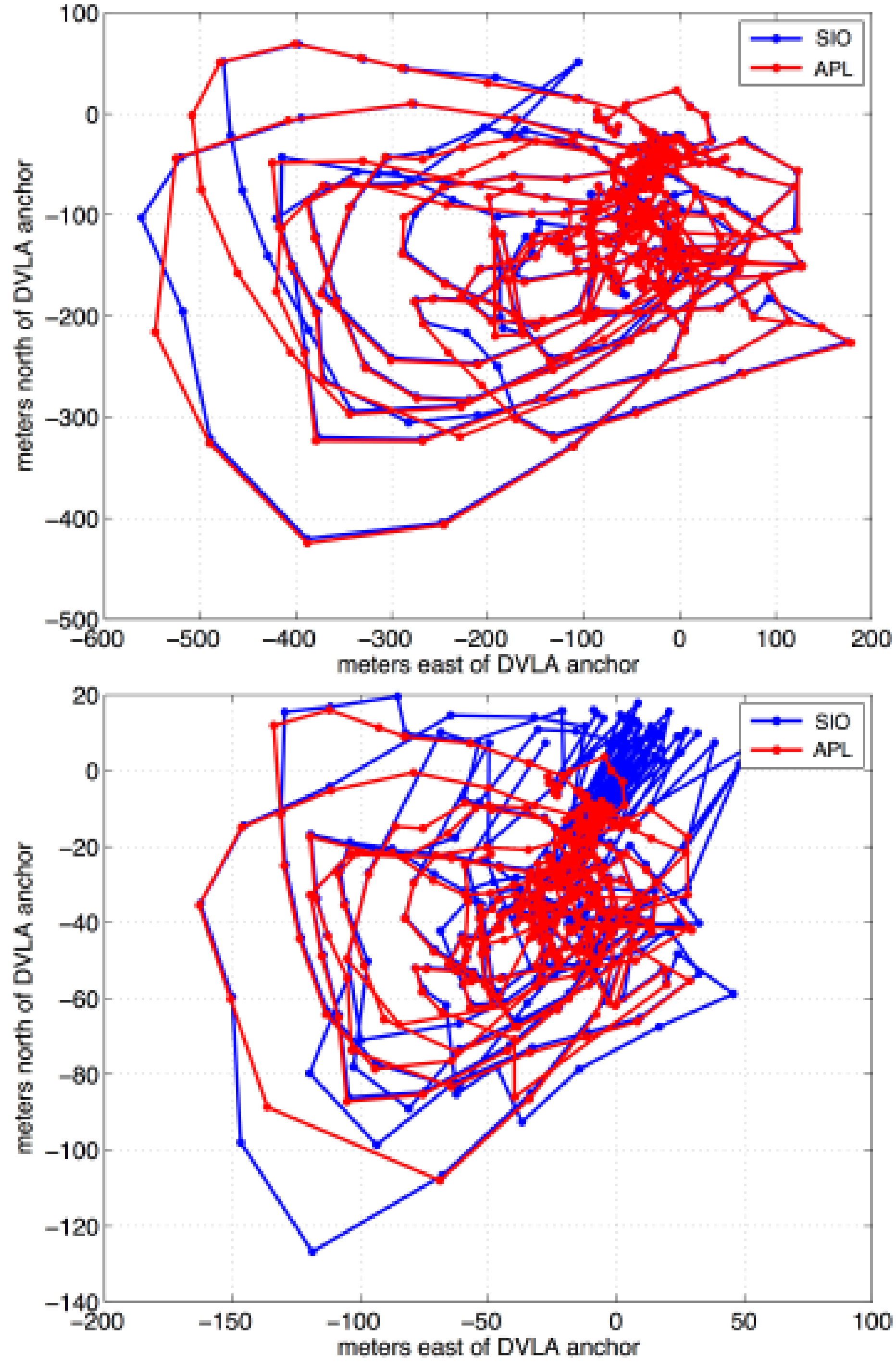


Figure 1: Navigation solutions for DSTAR controllers 0 (top panel) and 4 (bottom panel), over the period 08 May-2010 17:51:20 to 25-May-2010 22:51:20 (APL-UW operations only). Hourly position solutions denoted as dots, which are connected with line segments. The blue curves are the original solutions from SIO, and the red curves are the APL solutions.

```
>> theNavigator = CSIOVLA2010Navigator;
>> theNavigator = set(theNavigator,'Datafile','siovla.nc');
>> theNavigator = load(theNavigator);
>> tt = ['2010/05/08:21:50:15'];
>> t = get(theNavigator,'APL2Unixtime',tt);
>> r = get(theNavigator,'position',031,t);
```

Figure 2: Example Matlab code for interfacing with DVLA navigation solutions. Output variable* `r` *contains* $\{x(t), y(t), z(t)\}$ *for time 2010/05/08 21:50:15 UTC for hydrophone module S/N 031.

APL transmitted to the VLA, in order for us to visualize and identify any interfering acoustic events. Second, he built a "database" for post-processed data products related to the APL PhilSea2010 acoustic experiments for sharing among researchers. Since the APL experiments utilized (after pulse compression) pulsed interrogation of the ocean, the primary database elements are the pulses themselves:

pulse record:
- hydrophone S/N
- ray ID
- UTC timestamp
- signal type and sample rate
- complex pulse waveform
- quality code

Associated with each pulse record is a nearby measure of ambient noise, for SNR considerations:

ambient noise record:
- hydrophone S/N
- UTC timestamp
- noise level

We can also associate the VLA navigation correction associated with each pulse record, in case this is needed:

navigation record:
- hydrophone S/N
- UTC timestamp
- navigation correction

To date, two databases have been created: (1) the "red" multiport signal (based on raw VLA data already processed by Ganse yielding approximately 9000 timefronts, roughly 6 distinct pulses per timefront per hydrophone); (2) the corresponding 'red" Monte Carlo PE signal (approximately 240 independent realizations, courtesy of Dr. Andrew White, APL.) Four additional databases are planned: the "violet" multi-port signal (processing by Buck) and associated Monte Carlo PE simulations (already completed by White) , and the HX554 signal (Buck) and associated Monte Carlo PE simulations (White).

The database is implemented entirely in Matlab and is therefore completely portable.

North Pacific Ambient Noise Laboratory

- We moved our hardware laboratory to a new room at APL.
- We moved our CUI Data Center to a new room at APL.
- We moved our Secure Data Center to a new secure room at APL.
- At the request of NAVOCEANPROFAC, we removed all our APL equipment from a blockhouse in Coos Bay, OR.
- Last year, we re-purposed a remote site data collection computer for data archiving in our Data Center. This computer proved too old and slow for the job, so a node from our Bluewater cluster was re-purposed. This computer has an Intel Q6600 Core 2 quad processor running at 2.4 GHz with 6 GB RAM and is additionally outfitted with both a LG Super-multi DVDRAM for burning the "1000-year" M•DISC DVDs manufactured by Millenniata[5] and a Kingwin mobile IDE rack attached via a StarTech PCIIDE2 adapter for accessing the removable data hard drives used at our remote sites. This computer will support the download of significant quantities (nearly 1 TB) of back-logged data (basically 2009-present) that have been retrieved from the remote computers and are queued up for post-processing.
- We authored a new procedure document for removing unclassified ambient noise PSD data from the secure computers in our Data Center. This procedure was authorized 10+ years ago and used for more than a decade, but changes in security personnel forced us to resubmit the procedure for approval.
- We met with Christine Mire and Lisa Pflug of NAVOCEANO and discussed mutual ambient noise interests. They are very keen to add our PSD data to their database. The APL datasets for four systems are complete, but located on a classified computer: authorization delays stalled efforts to send these data to NAVOCEANO. Instead, as a trial, we sent them an old one-month data file from Pt. Sur for them to come up to speed on the details of handling these netCDF file formats within Matlab.
- We met with N2N6F24 to discuss the status of authorization for the NPANL ambient noise collections. Related to this, we researched our old ATOC files and assembled a package of relevant CNO letters, emails and agreements to support an N2N6 inquiry into the current status of our collection program.
- We began the effort of re-archiving all the ATOC/NPAL/NPANL optical media. Some of these discs are 15+ years old, and there is a considerable concern that some of these data could "evaporate". (Low-cost organic dye optical media is thought to have a shelf-life of about 3 - 5 years.) The first step in this process loads the data onto the computer hard drive. The data are reorganized into DVD-sized directories, effecting a compression for the early CDs of about 7 input discs to 1 output disc. The second step is burning the content to fresh DVDs. We are archiving first to low-cost organic media, and will follow up archiving to inorganic "1000-year" M•DISC DVDs. The archive is shown in Fig. 3.
- We were invited to give a lecture at an ambient noise workshop sponsored by the International Whaling Commission in Leiden, Netherlands on the subject of issues regarding long-time series data collection.

Figure 3: The aging collection of NPAL/NPANL optical media in the APL Data Center.

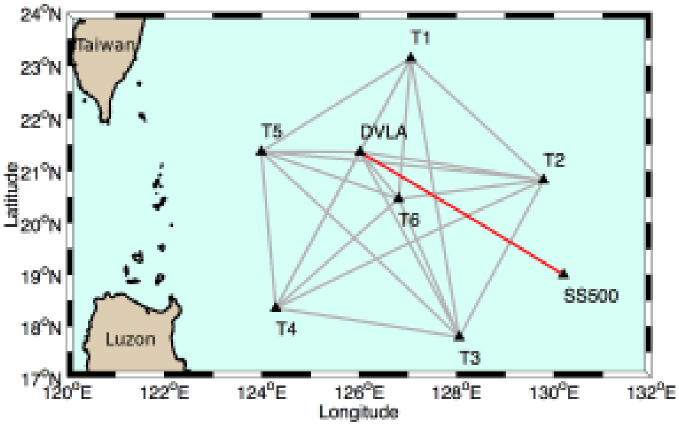
- We received a request from Stephen Nichols, Penn State, for an hour-long example of NPANL single channel omni-directional time series. We will need to build time-domain recalibration software to support this request.
- We received a request from Prof. Karim Sabra, Georgia Tech, for long (multi-hour) NPANL single channel omni-directional time series. We will need to obtain authorization to collect this kind of data but may be able to handle this entire request through classified channels, obviating the need for data downgrading procedures.

RESULTS

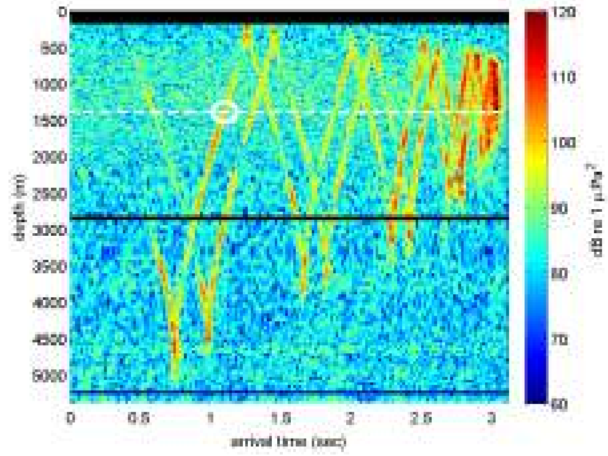
Philippine Sea Analysis

- *Saturated scattering without micro-multipath interference in 500 km acoustic transmissions in the Philippine Sea 2010 experiment*

  One of the major scientific interests in the ocean acoustic research community is to better understand the limits of fluctuation theories for long-range ocean acoustic scattering, which seek to explain the phenomenon of deep fading in long-range ocean acoustic propagation. Receptions of APL-UW transmissions at 200 Hz across 500 km in the Philippine Sea 2010 experiment (see Fig. 4) show apparent conflicts between measurements of ocean acoustic scattering effects and effects predicted by the commonly accepted micro-multipath explanation for them (see e.g. [6]. We analyze acoustic intensities and pulse spreads in these measurements to test the claim that micro-multipath interference is the physical process underlying deep fading in real-world ocean acoustics. This work is in two parts, one involving a deconvolution analysis to analyze the effects of noise on the problem, and the other examining histograms of measured acoustic intensities which are selectively filtered by their associated measured pulse spreads. Results for a single arrival on a single hydrophone are shown here, but results are similar on many other arrivals and hydrophones in the data.



(a)



(b)

Figure 4: (a) Experiment geometry – the ship-dipped source (at "ship stop 500km", or SS500) at 998 m depth transmitted continuously for 54 hours to 149 hydrophones which covered most of the ocean depth along the DVLA, 510km away. (b) Measured acoustic wavefront showing acoustic intensities of a single pulse-compressed M-sequence, multiport "red" signal; results for the white-circled arrival are shown in this report.

Micro-multipath theory (e.g. [6]) says that micro-multipaths, or splitting arrivals in the random medium, deconstructively interfere with each other to cause the deep acoustic fading seen in long-range ocean acoustic measurements. Various definitions of deep fading exist in the community; here we shall rely on that within Flatté's and Dashen's work, where an acoustic timeseries in which the lowest intensities are the most common is said to be deeply fading. The exponentially distributed intensities associated with saturated scattering in single phase screen theory (e.g. [8]) are said in their work to occur in real-world ocean acoustics due to deconstructive interference of many micro-multipath arrivals.

For deconstructive interference to occur, two or more micro-multipath pulse arrivals must be separated in time by at least a half carrier period. As the time separation between pulses increases, the intensity of their sum fluctuates with the interference pattern, and the width of the total pulse increases according to the time separation of the constituent pulses. If the width of the summed pulse is not greater than that of the individual pulses by at least half a carrier period, then the constituent pulses cannot be separated by that much, and deconstructive interference cannot occur.

The constant pulse width of the transmitted pulse is subtracted from the problem to focus on *pulse spread*, the difference between received and transmitted pulse widths. The fluctuating measured pulse spread $\delta W_{\mathrm{m}} = \delta W_{\mathrm{o}} + \delta W_{\mathrm{n}}$ is expressed in terms of a random pulse width fluctuation δW_{o} due to the oceanic fluctuations, and a random pulse width fluctuation δW_{n} due to ambient noise. The PDF of the pulse spread δW_{m} is the convolution of the PDFs of δW_{o} and δW_{n}. Given the PDFs of δW_{m} and δW_{n} we can deconvolve the ocean fluctuation component δW_{o}, and can then more meaningfully compare the measured mean pulse spread due to the ocean fluctuations to the half carrier period and to theoretical predictions of the CAFI path integral code [7]. Fig. 5 and its extended caption explain the deconvolution details and associated results. In these results note the

vast majority of pulse spreads due to ocean fluctuations are much less than a half carrier period, as are the means of those pulse spreads, as well as the pulse spread predicted by CAFI.

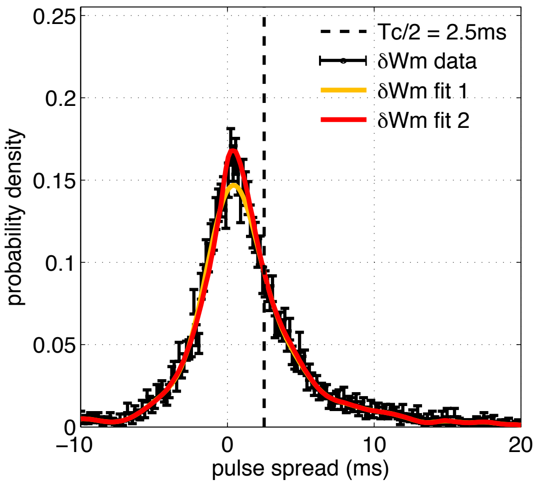
Like the pulse spreads, intensities of the acoustic arrivals also fluctuate over the timescale of the experiment. Unfortunately the inverted δW_{o} pulse spreads cannot have acoustic intensities paired with them like the measured pulse spreads do. So to compare intensity results with pulse spread results we must now leave the deconvolution analysis behind and return to the measured pulse spreads δW_{m} for further analysis. The detailed caption of Fig. 6 explains the histograms of acoustic pulse intensities selectively filtered by their associated pulse spreads. Those results show that histograms of measured intensities selectively filtered by measured pulse spreads are still near-exponentially distributed, even when spreads are much too small for deconstructive interference to be taking place.

In summary, the intensity and pulse spread statistics for 500 km ocean acoustic transmissions at 200 Hz fundamentally conflict with the commonly accepted micro-multipath explanation for deep fading in long range ocean acoustics, albeit without any obvious explanation in its place. The data consistently show near-exponentially distributed acoustic intensities such that the lowest intensities are the most frequent, even though the mean and majority of the associated pulse spreads are too small to cause deconstructive interference.

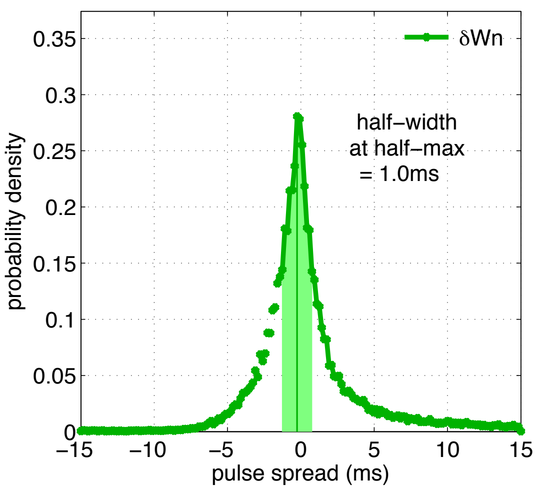
A manuscript presenting these results is in preparation for possible submission to *JASA Express Letters*.

- We compared the Henyey-Reynolds internal wave simulation code [3] to the Colosi-Brown internal wave simulation code[4]. In particular, we computed the statistic $n(z)\langle\zeta^2\rangle$ where $n(z)$ is the buoyancy frequency profile and ζ is the (zero-mean) vertical displacement due to internal waves. According to WKB theory, this quantity should be constant with depth with value 0.27 m^2/s. Fig. 7 shows the Henyey-Reynolds results versus depth for five random number generator seeds. For comparison, the same quantity was computed for five simulation runs from the two Colosi-Brown algorithms. Both Colosi-Brown algorithms perform essentially identically, and are about 20-25% low throughout the main sound channel.

  The reason that the Henyey-Reynolds algorithm achieves the WKB results but the Colosi-Brown algorithms do not is related to the region of integration in the horizontal wavenumber domain. These regions of integration are shown in Fig. 8. A fundamental feature of this model is that the internal wave field is horizontally isotropic, and this is reflected in the Henyey-Reynolds model explicitly by an annular region of integration. The Colosi-Brown specification results in separate rectangular integration “blocks” in each quadrant. (The block-like structure in the Colosi-Brown algorithm facilitates a fast computation via a 2D FFT.) Both algorithms have a hole at the wavenumber origin. The Henyey-Reynolds algorithm applies a correction for this hole, whereas the Colosi-Brown algorithm does not. Since the Garrett-Munk spectrum reaches its maximum at low wavenumbers, the lack of a correction in the Colosi-Brown algorithm for the hole results in the discrepancy from the WKB result.



(a)



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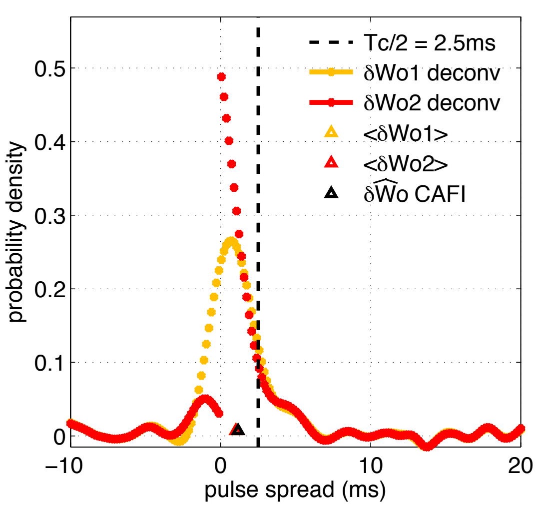


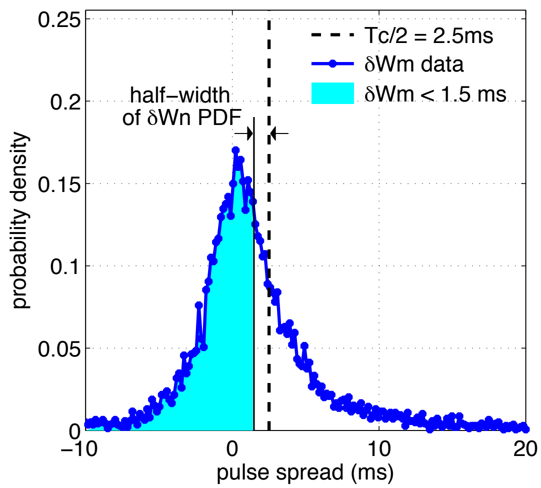
(c)

Figure 5: PDF deconvolution analysis to separate noise effects from ocean effects on pulse spread. Results shown for arrival ID +17 (first non-bounce arrival) on hydrophone #057:

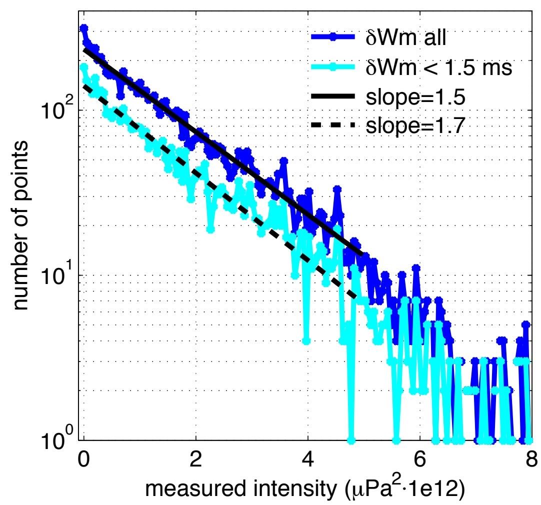
(a) The two deconvolutions both equally well fit the PDF (normalized histogram) of measured pulse spreads δW_{m} to within the Poisson-distributed sampling error, which is approximated as Gaussian because the histogram contains 8694 samples (error bars in plot represent ± 1 standard error).

(b) The noise-only component of the pulse spreads δW_{n}, generated via Monte Carlo ($N = 43470$) to simulate noise that was measured at the receivers. This noise kernel is deconvolved from the PDF of measured pulse spreads δW_{m} shown in (a). The half-width at half-max of the noise kernel is relevant to the selective filtering of pulse spreads in Fig. 6(a).

(c) Two deconvolution solutions representing ocean-only components of pulse spreads δW_{o}, for two choices of regularization. The deconvolution is ill-posed so regularization is required. Solution 1 used second-order Tikhonov smoothing; solution 2 used the same smoothing with a break at zero, plus a preferred model with no negative pulse spreads (a "suggestion" to the estimation process when the solution is not constrained by the data). Expected values $\langle \delta W_{\mathrm{o}1} \rangle$ and $\langle \delta W_{\mathrm{o}2} \rangle$ of the two solution PDFs overlap at 1.2ms, as does the CAFI-predicted pulse spread $\widehat{\delta W_{\mathrm{o}}}$. Note these are all at about a quarter of the carrier period T_c, much less than the half carrier period (dashed line at $T_c/2$) required for deconstructive interference, the commonly accepted mechanism causing the fading. The deconvolution analysis also shows that the negative pulse spreads seen in (a) are due to noise effects. The two solutions in (c) demonstrate that the fewer negative spreads remaining in the deconvolved solutions are due to the limited resolution of the inversion imposed by the regularization, and perhaps also effects of minor theory error from modeling the problem as a convolution.



(a)



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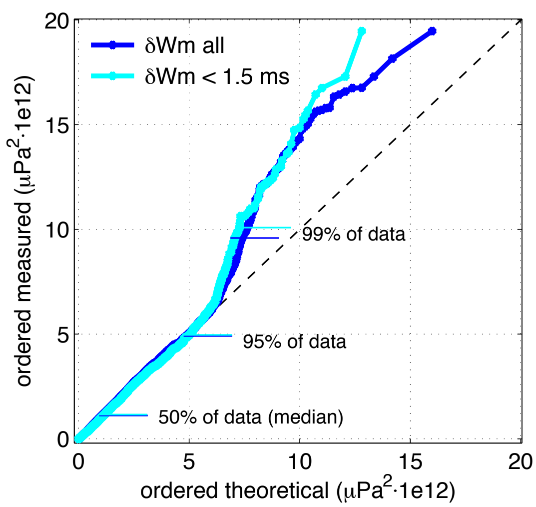

(c)

Figure 6: Histograms of measured intensities selectively filtered by measured pulse spreads are still near-exponentially distributed, even when spreads are much too small for deconstructive interference to be taking place:

(a) The measured pulse spreads δW_{m} include spreads $\geq$ half the carrier period $T_c/2$, so the complete dataset does potentially include fading caused by deconstructive interference. Thus we filter out measurements with those larger pulse spreads. The threshold is set at less than $T_c/2$, because as seen in Fig. 5 the noise effects contaminate these pulse spreads. (We cannot use the deconvolved solutions here because they do not have intensities paired with each pulse spread.) So the threshold is reduced by the half-width of the noise kernel in Fig. 5(b), to mitigate the noise contamination.

(b) Histograms of all measured intensities (dark blue), and of just the measured intensities with pulse spreads in the shaded region of (a), i.e. spreads less than 1.5ms (light blue). The intensities in both cases are near-exponentially distributed, even when no pulse spreads are anywhere near the half carrier period required for deconstructive interference. Fit lines estimating the slopes of the two histograms cover the lowest 95% of the intensities. Note there are a small number of data (few percent) with intensities greater than the upper boundary shown in this plot; the ranges of these are shown in (c).

(c) Q-Q plots for the two histograms match the measured intensities against a theoretical exponential distribution, and show that more than 95% of the data is quite close to exponentially distributed, confirming what is seen visually in (b). The remaining highest few percent of the intensity distributions are seen to be higher-tailed than exponential for this arrival/hydrophone, but this detail is not always consistent among other arrivals and hydrophones.

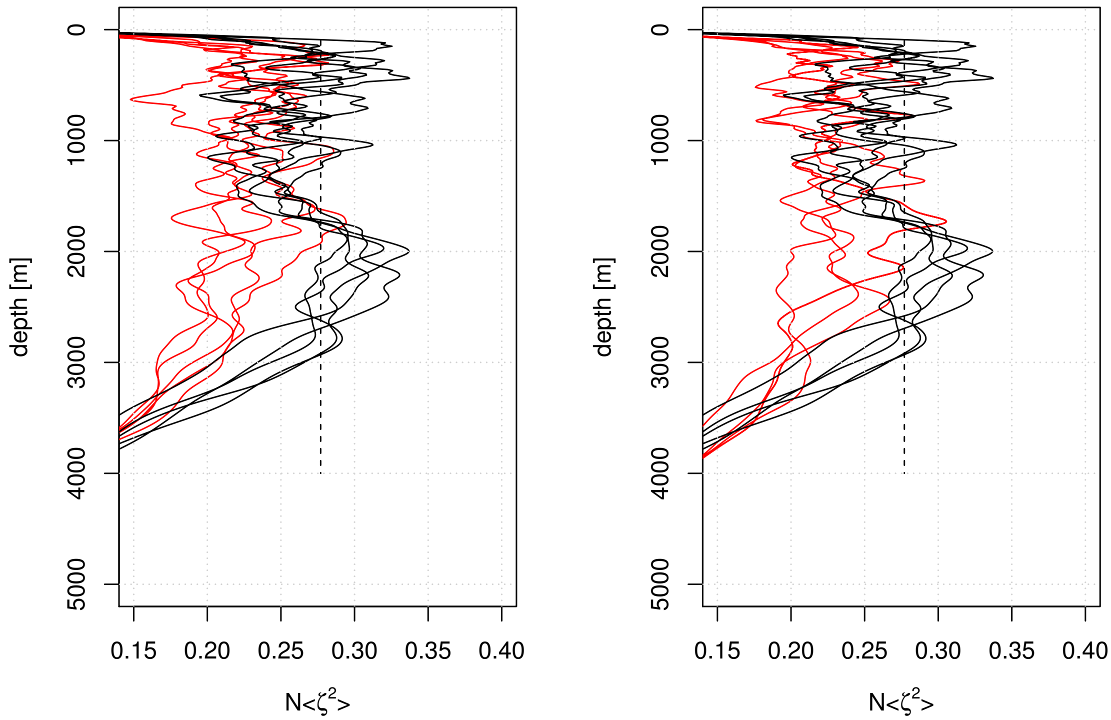

Figure 7: Comparison of the Henyey-Reynolds algorithm (black) versus the two Colosi-Brown algorithms (red). The two Colosi-Brown algorithms differ according to whether the randomness is in the phase (right) or in the amplitude (left). The ideal WKB result is shown as the dashed line.

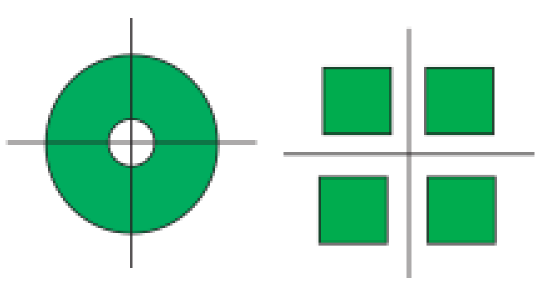

Figure 8: Horizontal wavenumber domains of integration. Left panel: the Henyey-Reynolds algorithm. Right panel: the Colosi-Brown algorithm. Both figures are representative only and neither is drawn to scale.

North Pacific Ambient Noise Laboratory

- We took advantage of the return of the DOS-based Kauai computer to APL for servicing to perform recalibration bench tests with it and the replacement Linux-based computer. The DOS computer uses the National Instruments AT-MIO-64F5 DAQ card, and the Linux-based computer uses the newer PCI-6071E DAQ card. The RMS monitor signal levels from both units were identical: the short-term RMS levels (i.e., from a AC voltmeter) were essentially identical, given that the observed levels vary randomly with time during the test by $\pm 10-20$ mV. Table 1 gives short-term RMS levels for typical measurements.

  The AT-MIO-64F5 output shows considerably more high-frequency noise, likely from DAQ on-board clock bleed-through. This is shown in Fig. 9. (The on-board clocks are in the megahertz range.) This is probably not an issue as neither the power amplifier nor the HX554 has any response at these frequencies.

  These test results[9] verify that the in-band monitor signal output of the replacement computer is equivalent to that of the current DOS computer to within engineering accuracy. The out-of-band noise (mainly high frequency cross-talk) is much attenuated in the replacement computer, likely because the replacement digital-to-analog hardware has a more modern design.

IMPACT/APPLICATIONS

- The evidence continues to support the hypothesis that the Philippine Sea provides stronger acoustical scattering than does the eastern north Pacific, where we have previously conducted long-range low-frequency acoustic experiments. While we suspected this, some of our models (the internal wave contribution based on density alone, or Munk-Zachariasen theory) continue to under-estimate the scattering strength, which will cause predictions of sonar and long-range acoustic communication performance to be overly optimistic in this regime.

RELATED PROJECTS

- Our deep water propagation efforts involve collaborations with Andrew White (APL), Art Baggeroer (MIT), Michael Brown (UM), Bruce Howe (UH), John Colosi and Tarun Chandrayadula (NPS), Vladimir Ostashev (NOAA/ETL), Ralph Stephen (WHOI), Alexander Voronovich (NOAA/ETL), Kathleen Wage (GMU) Peter Worcester (SIO), and Hee-chun Song and Gerald D'Spain (MPL). In particular, we worked closely with Dr. White to (1) estimate the PhilSea10 environmental parameters required for his Monte Carlo PE (MCPE) simulations of the PhilSea10 APL experiments, and (2) verify and validate his MCPE computations.
- Our expertise and experience in oceanic ambient noise continue to involve us in workshops focusing on the impact of ambient noise on the acoustic marine soundscape, and and invite

DOS Kauai	Linux CPU
$294\pm\approx 15$	$286\pm\approx 15$

Table 1: Output monitor signal level, old and replacement Kauai controller computers. Units are mV RMS. Errors are approximated by eye: during measurement, the reading jumps around a bit.

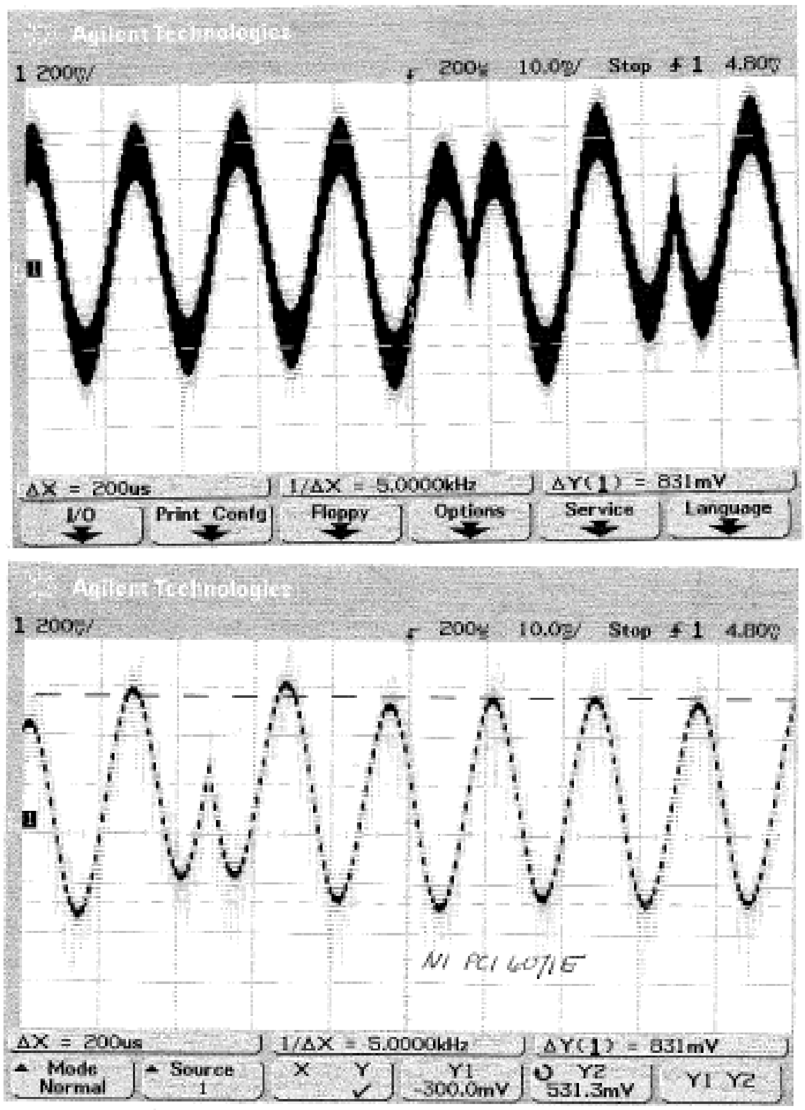

Figure 9: Scans of oscilloscope screenshots of monitor signal waveforms. Top: the AT-MIO-64F5 DAQ card in the DOS Kauai computer. Bottom: the newer PCI-6071E DAQ in the Linux computer. Note the thickness of the trace in the top plot: zoom resolution shows that this thickness is due to an additive high-frequency clock-like signal around 1 MHz or greater. The trace in the lower plot is much cleaner and therefore much thinner.

further collaborations (for example, Penn State University, Georgia Tech, and NAVOCEANO) involving new and unique uses of ambient sound.

- Our contributions to long-time trends in oceanic ambient sound have also connected us this year to Dr. Jennifer Miksis-Olds (ARL-PSU), Dr. Michael Ainslie (TNO), Prof. Michel André (Universitat Polytècnica de Catalunya) , Dr. Kevin Heaney (OASIS), Dr. Mark Prior (CTBTO), and Drs. Holger Klinck and Haru Matsumoto (OSU/NOAA) regarding global long time series measurements of ambient sound. This is in some degree a follow-on to the IQOE initiative of 2011, where most of us first synergized on this topic. An overview proposal titled "GLOSS: GLobal Ocean SoundScapes" and a planning letter titled "GLOSS: GLobal Ocean SoundScapes: Phase I Connecting the worlds oceans through sound" have been produced in order to solicit support via a wide variety of potential sponsors.

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AWARDS/HONORS/PRIZES

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